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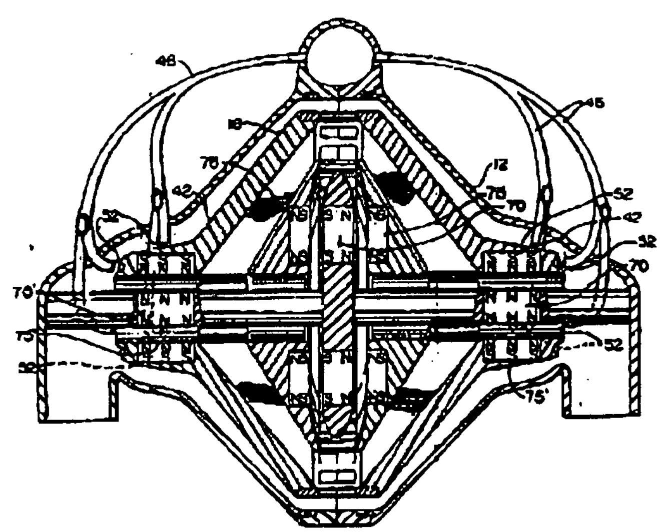

(57) Abstract

A fluid pump with a rotary impeller is disclosed which comprises an electromagnetically-driven, bearing-free, seal-free rotary impeller (16) levitated by localized opposed, magnetic forces and by fluid forces, or by localized opposed magnetic forces only. Levitation by localized opposed magnetic forces alone or by a combination of magnetic and fluid forces of an impeller driven by electromagnetic forces eliminates the need for bearings and seals in the driving mechanism. This avoids the heat build-up and leakage associated with other pumping mechanisms, which can be of importance in pumping of physiological fluids such as blood. The levitating forces of the present invention are applied both axially and radially with respect to the impeller. The magnetic forces are provided by a combination of diamagnets or solenoids (70, 70', 75, 75'), opposed by permanent magnets, solenoids or electromagnets (70, 70'. 75, 75'). The invention should be of use in numerous medical and non-medical applications where the benefits of impeller levitation by localized forces are apparent.

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DESCRIPTION

FLUID PUMP WITH IMPROVED MAGNETICALLY LEVITATED IMPELLER

RELATED APPLICATION

This application is a continuation-in-part of co-pending U.S. patent application Serial No. 07/774,034, entitled Fluid Pump With Magnetically Levitated Impeller, filed October 7,1991, now U.S. Patent No. 5,195,877 which is a continuation-in-part of U.S. patent application Serial No. 07/593,695, entitled Fluid Pump With Levitated Impeller, filed October 5, 1990, now U.S. Patent No. 5,055,005.

BACKGROUND OF THE INVENTION

This invention relates to a fluid pump with a rotary impeller. More particularly this invention relates to a fluid pump with a bearing-free, seal-free electromagnetically-driven rotary impeller. The impeller is levitated by a combination of axial and radial localized opposed magnetic and fluid forces or by axial and radial magnetic forces only. The magnetic forces used for levitation are generated by a combination of solenoids or diamagnets and permanent magnets, electromagnets or solenoids.

Levitation of the impeller by such forces allows for high efficiency in converting power into useful work. Thus, a relatively small energy source can be used and the life of the energy source is correspondingly extended. Moreover, use of a levitated impeller driven by electromagnetic forces eliminates the need for driving mechanism bearings and seals, thereby avoiding the heat build-up and leakage attendant with other rotary pump inventions. Such considerations can be of critical importance for pumping of physiological fluids such as blood.

A large number of mechanisms for pumping fluids have been described in the art, including, for example, peristaltic pumps, moving diaphragm pumps, piston-type pumps, and centrifugal or rotary pumps. Generally, a rotary pump includes a pumping chamber with inlet and outlet ports and an impeller mounted within the pumping chamber

for rotation about an axis. Frequently the impeller is mounted on a shaft that extends through one or more seals and a bearing apparatus to a rotational driving mechanism outside the pumping chamber. Rotary pumps employing shaft-mounted impellers with shaft seals are exemplified in the following U.S. patents: Dorman et al. U.S. Pat. No. 3,608,088; Rafferty et al. U.S. Pat. No. 3,647,324; Reich et al. U.S. Pat. No. 4,135,253; Clausen et al. U.S. Pat. No. 4,589,822; Moise U.S. Pat. No. 4,704,121; and Kletschka U.S. Pat. No. 4,844,707. Shaft seals are susceptible to wear and heat build-up, which can lead to leakage and, in the case of blood pumps, to thrombogenic (clot-forming) problems, denaturation of proteins, and embolic phenomena and the like.

Other pump inventions employ liquid or hydrostatic bearings to reduce heat build-up and/or to dissipate heat and to reduce frictional forces in rotation of the shaft and/or impeller. In these inventions liquid or gas is forced into narrow clearances between the shaft and various bearing assemblies or between the impeller and the impeller housing. The relatively thin fluid or gas films generated in these inventions are nevertheless subject to high shear forces and some incremental heat build-up. The following U.S. patents exemplify the use of such liquid or hydrostatic bearings: Prindle U.S. Pat. Nos. 845,816 and 888,654; Anderson U.S. Pat. No. 2,864,552; Baker et al. U.S. Pat. No. 3,122,101; and Kambe et al. U.S. Pat. No. 4,475,866.

Olsen et al. U.S. Pat. No. 4,688,998 discloses a fluid pump with an electromagnetically driven and levitated impeller. In Olsen et al., a sensor and a controller are provided to sense and control the amount of electromagnetic levitating force applied to the impeller. Only electromagnetic levitating forces are applied to the impeller. Unlike the present invention, in Olsen et al. the levitational forces are provided by electromagnets. In addition, in Olsen et al. the levitational forces are not applied to the impeller in separate and distinct axial and radial directions.

In the fluid pump disclosed in U.S. Patent 5,055,005, which is the grand parent of this application, while all the input energy is directed

to rotation of the impeller, a portion of the output energy from the peripheral region of the impeller (which includes locations downstream from the periphery of the impeller) is diverted for use in levitating the impeller by fluid force. Thus, not all of the input energy is directed toward pumping fluid from the pump. The fluid pump disclosed in U.S. Patent 5,195,877, which is the parent of this application is an improvement on the aforementioned fluid pump. In the fluid pump disclosed in U.S. Patent 5,195,877, the impeller is levitated and positioned in the fluid pump by auto-adjusting, permanent repulsive magnetic forces. This makes it possible for more input energy to be directed to rotation of the impeller and pumping of the fluid. The embodiment disclosed herein improves on the fluid pump disclosed in U.S. Patent 5,195,877, and employs a combination of permanent magnets, solenoids, electromagnets or diamagnets to levitate and position the impeller in the fluid pump.

SUMMARY OF THE INVENTION

In accordance with the present invention, a rotary pump is disclosed which is comprised of a housing defining a pumping chamber with one or more pumping chamber inlet ports and one or more pumping chamber outlet ports; a rotatable impeller or impellers disposed in the pumping chamber for rotation about an axis; polarized electromagnetic means for rotating the impeller about the axis; and opposed magnetic means located in the housing and impeller, respectively, such as a combination of diamagnets or solenoids in the housing opposed by permanent magnets, solenoids or electromagnets in the impeller for levitating the impeller axially, radially or both.

In the case of magnetic levitation of the impeller in the axial direction only or in the radial direction only, levitational forces in the other direction can be provided by fluid forces conducted from the peripheral region downstream of the impeller. Means is provided for conducting fluid from a high pressure area at the peripheral region of the impeller and for discharging the fluid in opposed directions within a

lower pressure area in general proximity to the axis of the impeller, in either an axial or radial direction. Thus the impeller is thereby levitated and stabilized within the pumping chamber by application of axial and/or radial fluid forces in combination with magnetic forces in the axial and/or radial direction.

The impeller may be fashioned of various materials, preferably nonmagnetic such as methyl methacrylate. Preferably, the impeller has an overall bulk density similar or identical to that of the fluid being pumped. This results in suspension of the impeller in the pumped fluid and facilitates levitation and stabilization of the impeller within the pumped fluid.

The impeller may take various shapes, and may or may not have vanes, depending upon the particular pump application. The impeller may be solid, or may have internal fluid-filled space in communication with the pumping chamber or with the pumping chamber inlet and/or outlet ports. The impeller may have a single inlet or opposed inlets near the axis of the impeller communicating with the pumping chamber inlet ports, and opposed outlets at the periphery of the impeller communicating with the pumping chamber outlet port or ports. The impeller preferably has axially extending neck portions.

Magnetic stabilization or levitation is achieved by magnetic forces in balanced opposed axial and/or radial directions. A plurality of magnet means is preferably located in the housing in magnetic communication with a plurality of magnet means located in the impeller. These magnet means are arranged both axially and radially with respect to the impeller for magnetic stabilization both axially and radially. The magnet means may also be arranged only axially or only radially for magnetic stabilization in only the axial direction or in only the radial direction, in which case stabilizing forces in the other direction can be provided by fluid forces.

In one embodiment, the housing comprises a central frame about which the impeller rotates. Magnet means may be placed in this

central frame so as to be in magnetic communication with the magnet means located in the impeller.

The magnetic forces are provided by a combination of, diamagnets or solenoids, opposed by permanent magnets, electromagnets or solenoids. The opposing magnet means may be disposed with the polarity of the opposing forces oriented to either repel or attract. Balanced repulsive magnetic forces are preferred when one of the magnet means is a diamagnet. Either balanced attractive magnetic forces or balanced repulsive forces may be used when one of the magnet means is a solenoid. If a diamagnet and a solenoid are used in combination, preferably balanced repulsive magnetic forces are used. When solenoids are used to provide the magnetic flux, sensors and a control system are required to control the amount of electricity sent through the coils of the solenoid to vary the magnetic flux.

In the case of magnetic stabilization in one direction (axially or radially) only, stabilizing forces in the other direction (radially or axially) can be provided by means of conduits emanating from the vicinity of the pumping chamber outlet port and terminating in various configurations generally near the axially extending neck portion of the impeller which conduct fluid forces to the impeller for impingement on the impeller. Thus, magnetic forces, or fluid forces together with magnetic forces, cause levitation of the impeller.

Polarized electromagnetic means for rotating the impeller may comprise electrically conductive wire windings within the periphery of the pump housing electromagnetically coupled to permanent magnets housed within the periphery of the impeller. Alternatively, the polarized electromagnetic means for rotating the impeller may comprise electrically conductive wire windings housed within a stator located internal to the impeller, the stator being in structural communication with the pump housing and electromagnetically coupled to one or more magnets housed within the internal structure of the impeller.

As used herein the term "fluid" means any aggregate of matter in which the molecules are able to flow past each other without limit and without the formation of fracture planes. The term includes gases, liquids, solutions, suspensions, slurries and gels and includes such specific substances as blood, plasma and serum.

BRIEF DESCRIPTION OF THE DRAWINGS

The above and other objects and advantages of this invention will be apparent upon consideration of the following detailed description, taken in conjunction with the accompanying drawings, in which:

Fig. 1 is an axial sectional view of a preferred embodiment of the present invention where axial and radial levitation is achieved solely by opposed magnetic forces;

Fig. 2a is a cut-away view of the preferred embodiment of the present invention, showing the orientation of one set of magnetic means in the housing and impeller, respectively, to provide axial levitation, taken in the region 2 shown in Fig. 1.

Fig. 2b is a diagramatic view of an embodiment of the present invention in which the opposing levitational magnetic forces are provided by helically wound solenoids radially spaced about the axis of rotation of the impeller. In Fig. 2b each pair of opposing solenoids is disposed on a common radial axis.

Fig. 2c is a diagramatic view of one pair of opposing toroidal solenoids in which the respective coils are each helically wound about a circular axis and the opposing coils are disposed in spaced parallel relationship on a common axis.

Fig. 3 is a cross-sectional view of the preferred embodiment of the present invention, taken on line 3-3 of Fig. 1 showing the orientation of another set of magnetic means in the housing and the impeller to provide radial levitation;